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Preparation of the Digital Elevation Model using open source Geographic Information Systems tools for 3D prints

Abstract. The presentation of landforms in two-dimensional graphics may not always be clear and understandable to every viewer. The presentation of landforms, as well as other types of characteristics and issues in three-dimensional space can bring many advantages in the process of better understanding of the surrounding reality. The primary purpose of this research is to put forward a simple scheme, accessible to any Geographic Information Systems user, for generating 3D physical terrain models for any area of the Earth. The presented scheme can be used anywhere in the world, however, for the purpose of illustrating its capabilities, a case study of a selected area – the Tatra Mountain range – was conducted in this paper. As part of the study, a 3D model was developed based on a Digital Elevation Model obtained from an open source, i.e. MapTiler. An indisputable advantage of the study is that the designed process flow in its structure takes into account only generally available tools and software (the model was prepared in the QGIS program). However, a certain limitation is the process of printing itself, which depends on the availability of specialized printing equipment. In this case study, FDM (Fused Deposition Modeling) technology was used for printing, and the model itself was prepared on a Creality Ender 7 printer. The proposed flowchart, on the one hand, unifies and simplifies the process of creating physical 3D models, while on the other hand, it provides opportunities for GIS users and developers to develop the proposed solution.

Keywords: Digital Elevation Model, Geographic Information Systems, open-source, 3D model, 3D printing

1. Introduction

Integrated studies related to the DEM (Digital Elevation Model) are nowadays used in the precise visualization of the earth's surface, and a good deal of attention is paid to ensure that such models represent the actual landform as accurately as possible (Habib et al., 2020; Mukherjee et al., 2013; Yamazaki et al., 2017). A DEM should be interpreted as a numerical presentation of the terrain surface, created on the basis of a set of defined points (XYZ) of the analyzed surface and interpolation algorithms that give the possibility to reproduce its shape in a specific area (Guth et al., 2021). The presentation of the terrain surface in numerical form is now widely used in spatial analysis, and the interpretation of the terrain with the use of DEM is the basis of analyses carried out, among others, by engineers, hydrologists, geographers, geomorphologists, but also by the military who depend the course of their tasks on the existing terrain (Chen et al., 2019; Dawid & Pokonieczny, 2020; Muthusamy et al., 2021; Polidori & El Hage, 2020; Zingaro et al., 2021). DEM presentation technologies have clearly evolved over the years, at the same time enabling far more accurate exploration and more precise knowledge of land surface phenomena (Mesa-Mingorance & Ariza-López, 2020).

Presentation of the terrain surface model in three-dimensional space can find application in quantitative and qualitative measurements that are difficult to obtain with traditional maps made in two-dimensional space (Kete, 2016; Lütjens et al., 2019; Rong et al., 2020). This situation is related, among other things, to the fact that the characteristics of terrain conditions due to the relief and scale of the terrain can be ambiguous and difficult to interpret accurately for the average user of such maps. DEM visualization in traditional 2D technology can be done using color "ramps" or appropriate isolines, among others (Galin et al., 2019; Mach & Petschek, 2007; Mitasova et al., 2012). Interpretation of height differences in a given area using isolines suggesting, among other things, the slope of a given terrain may be uncomplicated for specialists working with such maps (e.g., geographers or geologists), but non-specialists may often have trouble visualizing 3D terrain based only on the frequency of isolines or color found on the map (Lepczyk et al., 2021). The solution to the above problem can be 3D printed models, which directly provide universal knowledge about the relief of the earth's surface (Hasiuk, 2014; Walker & Humphries, 2019).

The term 3D printing encompasses a range of technologies for additively shaping a product (Anastasiou et al., 2013; Thakar et al., 2022). Nowadays, 3D printing technology is developing rapidly and is used in many fields including medicine, education, aerospace, architecture, construction and engineering (Oswald et al., 2019; Shahrubudin et al., 2019). Regardless of the 3D printing method applied, the technological process involves printing successive layers of the designed model usually in CAD software. These layers, can be printed using the following technologies, among others (Gołębiewski et al., 2024; Yan et al., 2018):

− SLA (Stereolithography) – printing with resins cured with laser light, the advantage is high printing resolution, sintering up to 1300 °C;

− SLS (Selective Laser Sintering) – printing with powdered building material that is sintered with laser light, product susceptible to cracking;

− FDM (Fused Deposition Modelling) – printing based on the production of a model from molten material (thermoplastic such as PLA – polylactide), the advantage is low cost, satisfactory strength and the possibility of using many materials, the scheme of operation involves melting the material and depositing it on the work table;

− 3DP (Powder bed and inkjet head 3D printing) – printing material selectively combined in a pattern based on the liquid binder of the print head, the problem can be contamination of the binder.

Nowadays, users on the market have access to dozens of printers working with specific technologies and characterized by different technological capabilities. The most important of the main components of printers that enable melting, sintering or bonding of material is the laser or head (depending on the printing system). The material itself used in the 3D printing process is of great interest to many researchers. As a result, it is increasingly common to find cases where materials such as polymeric composite materials or high-performance biodegradable materials are used for printing (Gu, 2016; Lyu et al., 2021; Wang et al., 2017).

To the best of our knowledge, a detailed (in technical terms) and comprehensive, yet modifiable method of combining the two environments Geographic Information Systems (GIS) and additive technology presented has not yet been included in any of the available studies on the subject. Little is known, also about exactly which tools make it possible to connect these two environments. Furthermore, according to our observations, there is no existing study that explains how to prepare a physical presentation of the terrain using the GIS environment on the basis of a DEM developed from own measurements. Using our scheme, users have the possibility to modify it, including the DEM used. Therefore, the most important goal of this research project is to present a simple, accessible scheme for generating 3D physical terrain models for any area on Earth.

There are several contributions this study makes. First, the proposed flowchart in its structure connects GIS with 3D printing technology. Second, the tools used in the application in question represent a modern, but also widely available approach in the process of preparing a physical 3D terrain surface model. Finally, a major advantage of the proposed flowchart is that the person preparing the physical model can fully intervene in the process. Thanks to the fact that individual stages can be defined as needed, the final model can have properties in accordance with the expectations of both the person preparing the model and the requirements of potential customers.

2. Flowchart and Study Site

2.1. Flowchart

The developed scheme is divided into 6 basic, necessary steps in the process of generating a physical presentation of the DEM. The main point of the presented flowchart is the link tool between the Geographical Information Systems environment and Additive Manufacturing.

In addition, supplementary steps are included in the presented scheme, which can increase the content value of the study and the quality of, but are not necessary for the complete process of generating 3D physical terrain models (Figure 1).

2.2. Study Site

The proposed scheme in this chapter is suitable for the preparation of 3D models on the entire surface of the Earth, but in order to demonstrate its capabilities in the work, a model was prepared for a limited area. The area for which the case study was carried out covered an area of approximately 1547 km^2 and included the highest mountain range located in the Carpathian chain, i.e. the Tatra Mountains, including the highest peaks in Poland (Rysy) and Slovakia (Gerlach) (Figure 2).

2.3. Materials

The primary source of information necessary to achieve the stated goal is the Digital Elevation Model, which can be obtained by various methods, from a variety of sources characterized by a specific mode of accessibility (Geymen, 2014; Wessel et al., 2018). In the following study, special attention was paid to accessibility, and for this reason, the information about the land surface elevation was obtained using a freely available tool (only free account MapTiler is required) available in the QGIS software environment: MapTiler (https://www.maptiler.com). This plug-in allows, among other things, to export a DEM for any area on Earth (Figure 3a, Figure 3c). The defined research object covered a total area of about 1547 km^2, the choice of such a large area was intentional as the specific

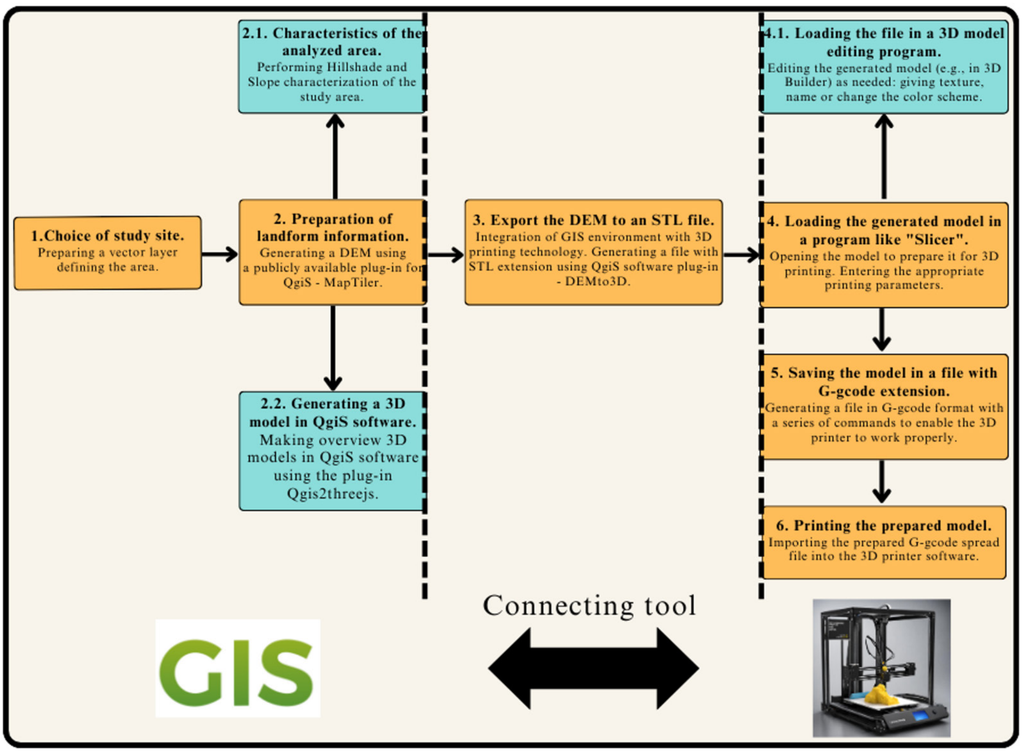


Figure 1. Diagram of the preparation of the physical presentation of the DEM

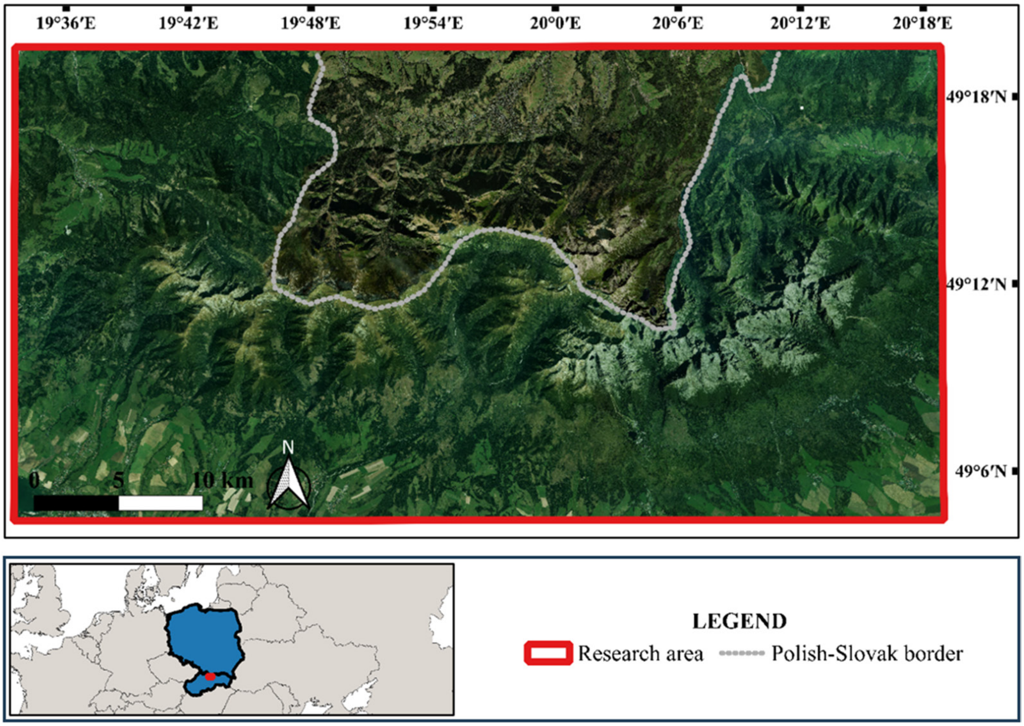


Figure 2. Study Site location

purpose of this study was to demonstrate the possibilities of 3D printing technology in the case of medium-scale maps. Some problems associated with the acquisition of surface elevation information for such a large area may be related to, among other things, the size of the output file and the accuracy of the generated raster. With the defined coordinates of the study area and a certain pixel size (0.4 m), the size of the generated DEM raster layer was about 36 GB. With a possible change of the pixel size to a larger value, the quality of the generated raster could visibly decrease. Maintaining the above-mentioned properties, the final DEM was generated using the open-source MapTiler tool (Figure 3b).

3. Model preparation

3.1. Description of proceedings in a GIS environment

The acquired source data was first subjected to additional characterization, which allows a more accurate interpretation of the analyzed terrain (not necessary in the process of preparing the model for 3D printing).

First, the relief of the area was imaged using the Hillshade tool. As a consequence of the use of this tool, a raster generated taking into account the location of the light source, i.e. the sun in relation to the analyzed area, was obtained. The location of the sun was defined by two values: the azimuth of the sun: 315° and the height of the light source: 45° (these values can, of course, be edited as needed). This raster represents in its structure the shadow that occurs in the area at the given parameters which consequently makes it possible to present a real, resembling with certain proportions 3D image of the relief (Figure 4a).

The Slope was the next tool included. It tells how steep and sloping an area is. This analysis is indispensable, for example, in the process of selecting a suitable site for housing projects. In addition, the analysis used shows the slope of the land in a much more accessible form than, for example, isolines (Figure 4b).

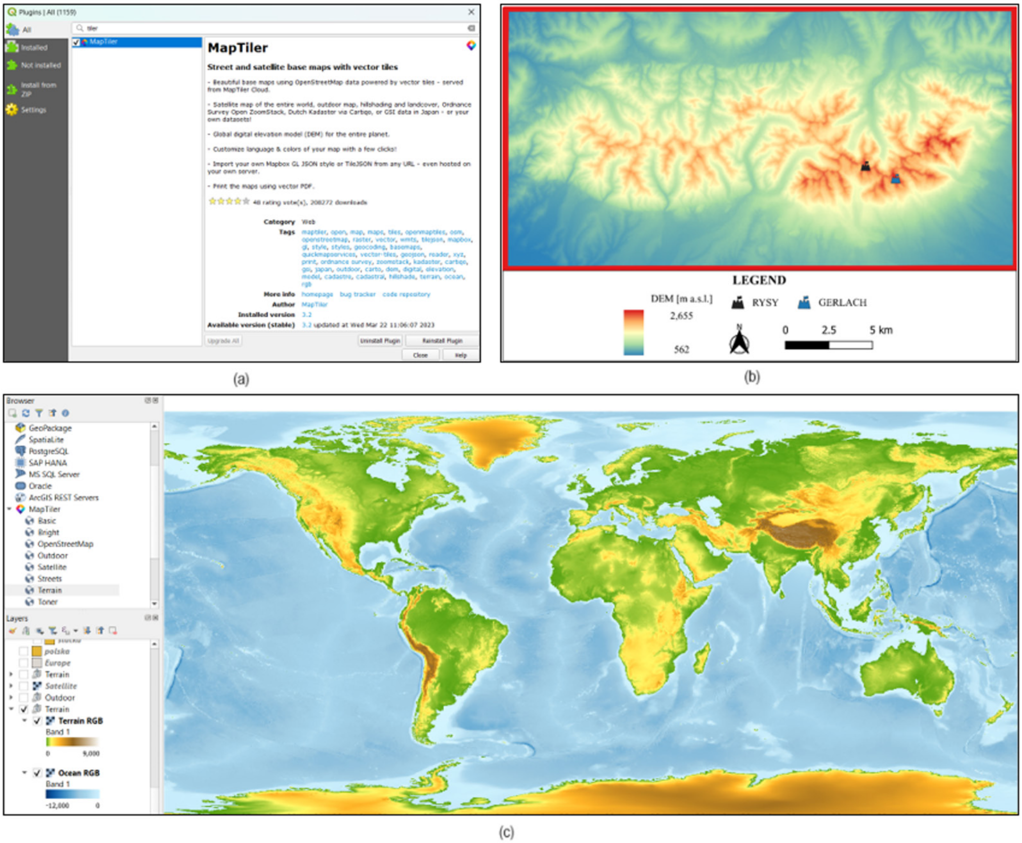


Figure 3. (a) Basic capabilities of the MapTiler tool; (b) DEM of the analyzed area; (c) DEM loaded into QGIS using the MapTiler plug-in

In the next stage, 3D overview models of the study area were made using a plug-in for the QGiS program: Qgis2threejs. This tool allows, among other things, 3D DEM visualization, preparation of 3D prints and export of models to web browsers (Figure 5a). The generated visualizations of the study area in the first step were made with an overlay, which was a previously prepared DEM. For a complementary representation of the model, it was shown from two perspectives (Figure 5b, Figure 5c).

A major and indisputable advantage of the presented tool is the possibility of automatic 3D visualization of a selected limited area. In addition, users have a wide range of possibilities when developing thematic maps, the overlay on the model can be, for example, open geographic databases (OpenStreetMap), satellite images or maps presenting other specific spatial characteristics (Figure 6).

A key step in the process implemented was to prepare the model for printing using a tool that was the first in the GIS environment to link it directly to 3D printing. The basic and only functionality of the DEMto3D plug-in is the export of rasters from the DEM to files with STL extension ready for 3D printing. The necessary step to start the process of generating the final 3D model is to indicate the appropriate raster layer and indicate the basic parameters of the model including its dimensions, scale, spacing (the program suggests the recommended parameter) and vertical exaggeration (Figure 7c).

The model thus exported can be subjected to certain modifications as required, including naming or changing the color scheme. These

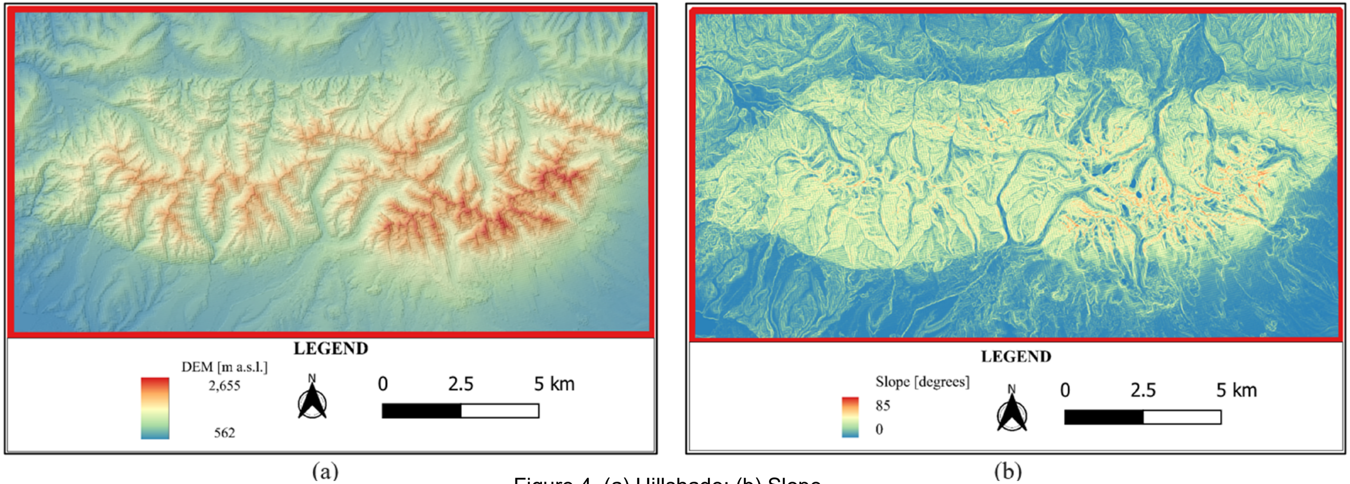


Figure 4. (a) Hillshade; (b) Slope

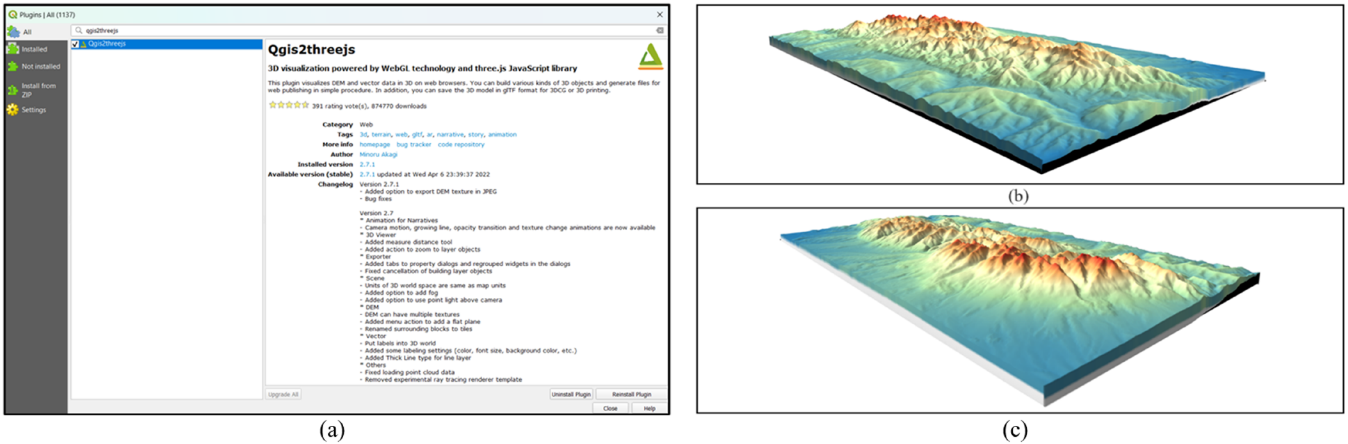


Figure 5. (a) Basic capabilities of the Qgis2threejs tool, 3D terrain model vertical exaggeration 1.5; (b) View of the model from the Slovak town of Tvrdošín; (c) View of the model from the Slovak city of Poprad

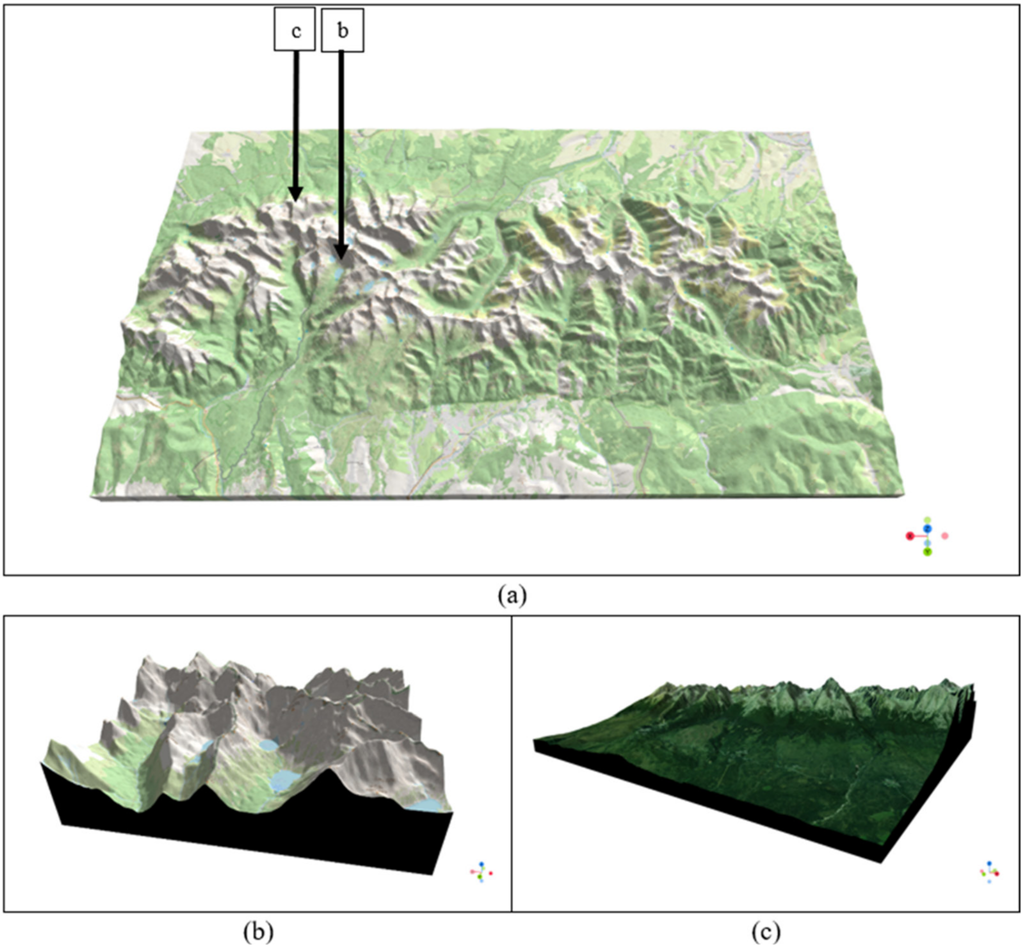


Figure 6. (a) 3D model of the entire study area with OSM overlay; (b) Part of the model with OSM overlay – vicinity of Morskie Oko lake; (c) Fragment of the model with overlaid satellite image – vicinity of Gerlach peak

transformations can be performed in any software with such capabilities. In the present study, a name was added to the final model, explicitly defining the study area. This modification was made in 3DBuilder software (Figure 7a, Figure 7b).

3.2. Description of proceedings in an additive technology

The last of the activities influenced by the user is setting the appropriate printing parameters in a program like Slicer. There are many software programs on the market that allow to "slice" 3D models into layers and indicate print settings, these include Cura, Simplify3D and Prusa Slicer. Due to the printer on which the final print was made (Creality Ender 7 – working in FDM technology), the generated model was prepared in dedicated Creality Print software (Figure 8).

The basic necessary parameters that need to be completed include the printing speed of the individual elements, the temperature of the head and table, the quality of the print defined by the layer height and the fill density (Figure 9d).

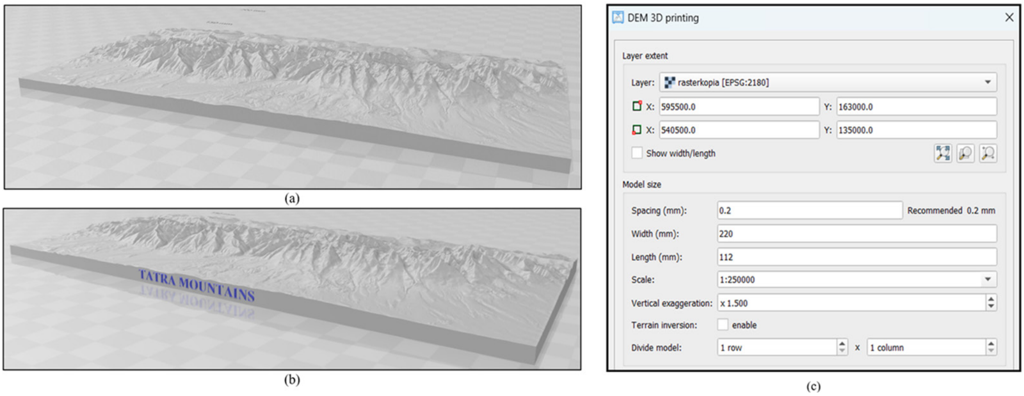


Figure 7. (a) Generated model; (b) Model edited in 3D Builder – embossed model name; (c) Basic settings – DEMto3D plug-in

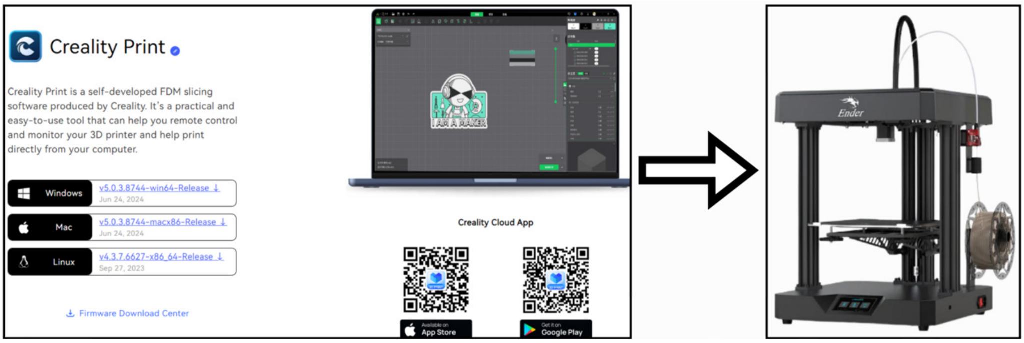


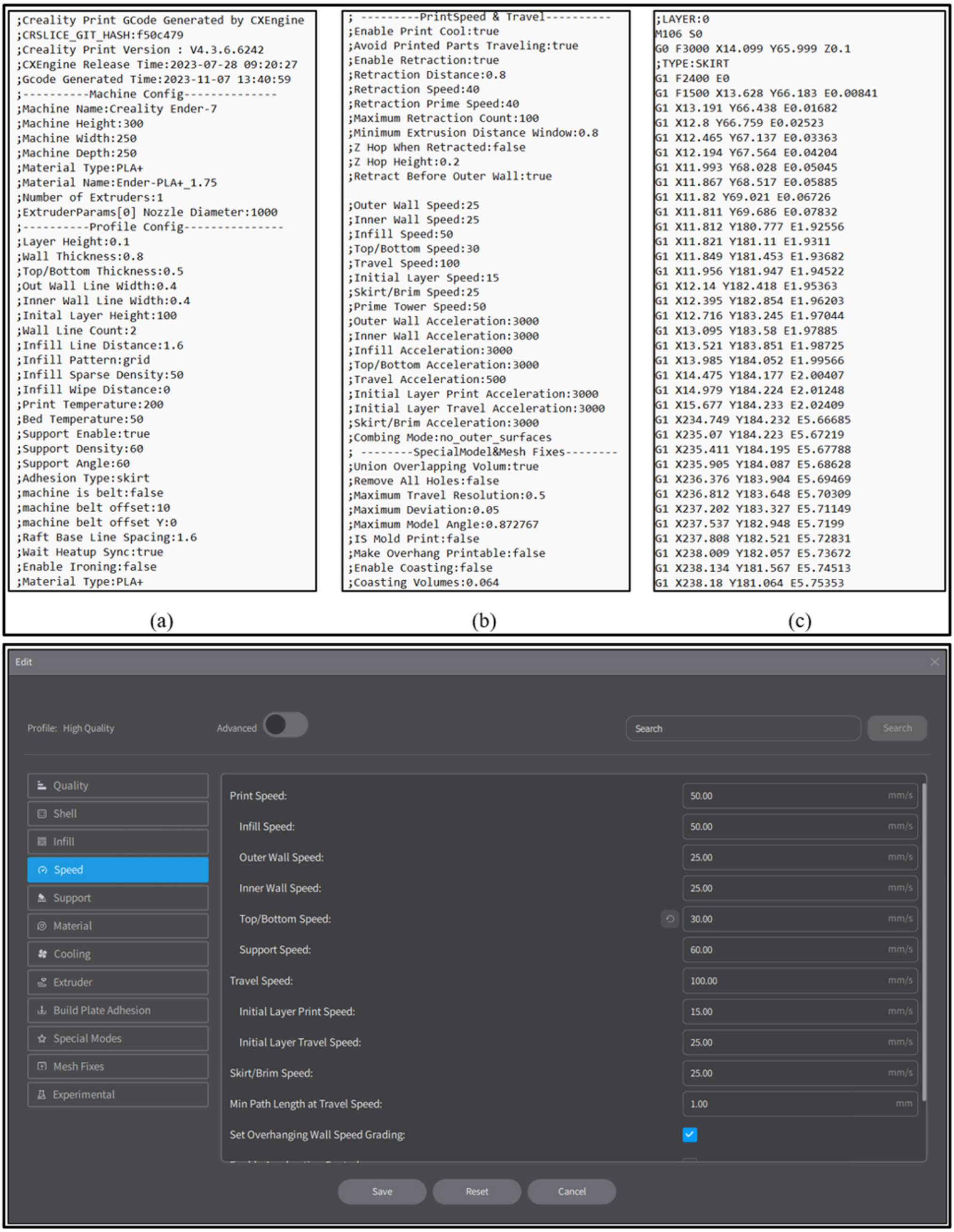
Figure 8. Software and printer used

It must be remembered that these settings should be adjusted to the printer's capabilities. After indicating the appropriate settings, the model can be sliced into layers, a file with the G-gcode extension is generated. This format is a kind of command language for, among other things, 3D printers working with FDM technology. The quintessence of the file saved in this extension are simple commands, which indicate to the printer the next actions necessary to print the model, such as warm up the nozzle to the set temperature, move the head to the right place or stop printing for a specified time. The G-gcode file can be opened in a text editing program such as Notepad. This property allows the user to modify it as needed. In the present study, the goal was not to show the possibility of modifying individual commands; therefore, the code, generated directly in the Creality Print program, was used for printing (Figure 9a, Figure 9b, Figure 9c).

The model prepared for printing (G-gcode) can also be activated in a program like Slicer, which at this stage gives the possibility to simulate printing (tracing successive printer movements) and estimate, among other things, the total printing time (Figure 10a). Taking into account the technological possibilities including the dimensions of the table of the printer on which the print was made (Creality Ender 7), the final model was prepared according to the dimensions selected during the export of the prototype from the QGiS program (Figure 10b).

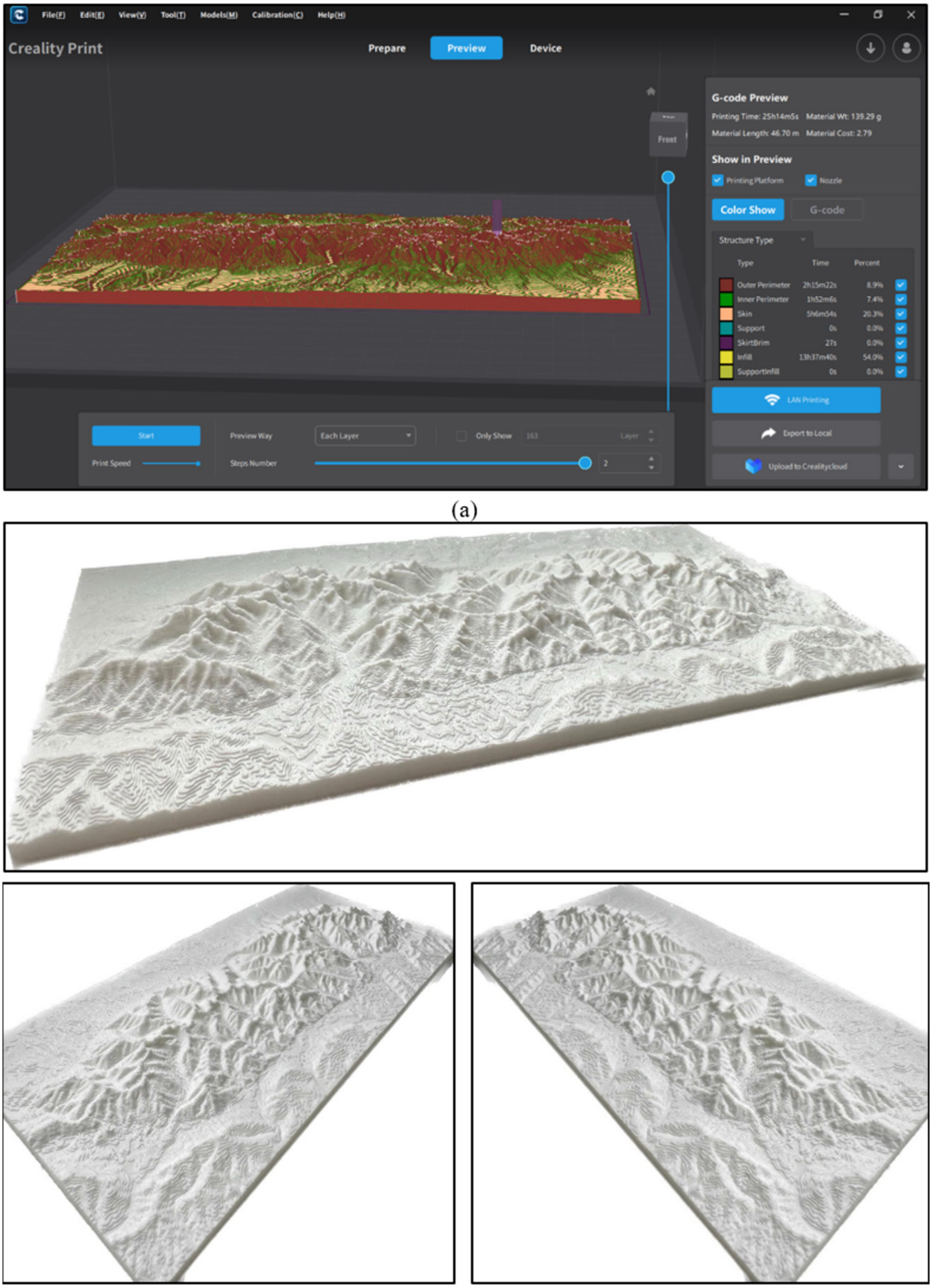
4. Discussion

In this paper, we have proposed a flowchart for generating and printing numerical terrain



(d)

Figure 9. Parts of G-gcode file used for printing: (a) Printer information, printing temperature; (b) Print speed; (c) Layer 0 print settings; (d) Basic 3D printing settings in Creality Print software



(b)

Figure 10. (a) Print-ready model, saved in G-gcode extension; (b) Printed model (from different angles) at scale 1:250,000, vertical exaggeration 1.5

models based on open-source data. The implementation of the procedure in practice is presented on the basis of a case study for an area covering a mountain range – the Tatra Mountains. A physical model constructed in a visually attractive way and in an accessible form presents the diversity of terrain in the selected area (at an appropriate scale). The presentation of the terrain in the form of a printed three-dimensional model provides not only information about the differences in height of a given area, but above all can be a kind of promotion of a given place as well as an element extremely important for the development of tourism in the region. The scheme developed for this study is characterized by a number of advantages and a few imperfections, which could be improved in subsequent work related to this issue.

First of all, the basic, undeniable advantage of the presented scheme is that it takes into account only open-source data in its structure. Based on the proposed solutions and tools, interested parties have the opportunity to prepare a model for any place on Earth, at the appropriate scale and with the expected parameters, i.e., among other things, the size of the model. In the literature, one can find studies of this type, but their disadvantage is the source material on the basis of which the models are developed. Some of these works are based on military elevation models (Wabiński & Kuźma, 2017) developed in the 1990s, while others on material recorded in resources available in databases available upon request (Wabiński & Mościcka, 2019) or in databases that only include DEMs for selected sites in their structure (Horowitz & Schultz, 2014). Considering the above information, we believe that on a global scale our solution can find wider application compared to the mentioned studies, and proposing the source material used by us can significantly contribute to the development of the analyzed process, i.e. creation of physical 3D models based on DEM.

In addition, with respect to comparable studies and proposed solutions (Harding et al., 2021; Hasiuk et al., 2017), our concept enables the user to customize their technological workflow to their specific needs, from selecting the area to making final changes to the printed model. For example, skipping the first two points of the flowchart will not result in an inability to prepare the model. A GIS user can prepare the DEM on his or her own, for example, using laser scanning, and then follow the further points. On the other hand, the solution proposed in the above-mentioned works is undoubtedly useful in the rapid preparation of many large-scale models, and can find application, among others, for those who do not work in a GIS environment. At the same time, it should be emphasized that a significant advantage of the cited TouchTerrain tool is automatic access to many DEM-related databases. This property undoubtedly increases its value, and the prepared models can be realized with a certain expected accuracy. On the other hand, its disadvantage, in our opinion, is the lack of possibility to configure the prepared model according to the needs, those wishing to make their own modifications do not have such an opportunity. An extremely important issue in the process of 3D map preparation can be the application of an appropriate texture to the model (e.g., orthophotomap, DEM or OSM), this matter in its structure is not taken into account both the referenced tool and other similar works (Zhang et al., 2020), which is, in our opinion, their biggest drawback.

In addition, our work can be of great benefit, as the structure of the proposed scheme has been described, and attention has been paid in the research to elements often overlooked in the cited previous works within the literature, i.e., for example, the structure of the command language for the G-gcode printer. Ultimately, our solution based on tools such as DEMto3D or Qgis2threejs is a new concept, described in the literature in only a few studies (Chandra et al., 2022, p. 36; Solla et al., 2020). Systematizing and expanding the knowledge of the possibility of using free tools in the process of preparing physical 3D models can bring many positive aspects to the integration of the GIS environment with 3D printing technology.

Unfortunately, despite the advantages of the proposed scheme, it obviously has some technical limitations. First, exporting a DEM using the MapTiler tool for large areas involves the fact that with certain settings the resulting raster can be of considerable size. This situation can affect not only the time of its generation itself, but also the need to store them on external disks. Moreover, the disadvantage of the structure of the study itself may, for some readers, be the lack of an estimation of the accuracy of the printed model similarly to the proposed estimation in one of the earlier studies (Wabiński & Mościcka, 2019). However, we came to the conclusion that the accuracy of the printed model itself may be directly dependent on the printer used and therefore such an assessment was not performed. Finally, applying a map underlay to the final printout would also increase the attractiveness of the study, but with regard to the most important objective and the availability of technological possibilities, we decided not to make a printout with additional elements. These issues are, in our opinion, important, but do not prevent the accomplishment of the set research objective. Taking them into account in future research work can improve their quality and will undoubtedly be an issue that will become increasingly important in modern times.

5. Conclusions

The rapid development of 3D printing technology now makes it possible to apply it to many areas of life and science. This development can be enhanced by attempting to link this technology with other scientific disciplines and identifying viable applications of the technology. With regard to this issue, in our work, we have attempted to present a simple-to-apply scheme for combining Geographical Information Systems with Additive Technology. Our primary objective was to present a scheme that can find many applications, in the work this scheme was simultaneously supported by a case study.

From our point of view, the proposed scheme extends the existing state of knowledge in this field and, in addition, provides valuable information on the technical aspects of preparing 3D physical terrain models. Our research has considered most of the issues that were address by few existing studies related to the physical presentation of the digital terrain model but in our point of view the technical issues we raise make an important contribution to the popularization of 3D printing. The presentation of the current possibilities of using tools generally available in the GIS environment with 3D printing technology represents a novel approach in this field.

Furthermore, the method presented is very flexible. It can be edited and configured according to the users' needs. Such an approach may help to increase interest in 3D printing technology and attract the attention of GIS users to this technology. Expanding interest can only contribute to the field of science in question.

Undoubtedly, the models of the future should also include interactive elements that can enhance their accessibility for everyone. Further development of 3D printing should therefore focus on integrating prepared models with, among other things, sound elements that could describe the individual elements of the model. We consider that thanks to its characteristics, the workflow proposed in this work opens several additional avenues for future research related to the development of the use additive manufacturing in the process of thematic map creation.

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